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SHORELINE EROSION: A CAUTIONARY NOTE IN USING SMALL FARM DAMS TO DETERMINE CATCHMENT EROSION RATES

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ABSTRACT

Data from 10 small farm dams in SE Australia show that shoreline erosion due to farm livestock access to the dams can account for a significant proportion (up to 85%) of sediment contained in the dam. The volumes of sediment resulting from such shoreline erosion may be of the same order as the volumes produced by gully erosion in the dams' catchments, prompting caution in using farm dams to which livestock have access to determine small catchment erosion rates. Other issues, related to the trap efficiency, also mean that erosion estimates based on farm dam sedimentation should be treated with caution. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: erosion rates; dam sedimentation; shoreline erosion; cattle; trap efficiency

INTRODUCTION

Understanding and quantifying erosion remain two central and interrelated issues in geomorphology, and much effort is expended on elucidating the sources of eroded sediment and the rates at which this sediment is being eroded. Two techniques that attempt to quantify rates of erosion, namely the determination of either the volumes of sediment trapped in impoundments (e.g. Langbein and Schumm, 1958; Le Roux and Roos, 1982; Wasson and Galloway, 1986; Wasson *et al*., 1987; Neil and Galloway, 1989; Neil and Fogarty, 1991; Neil and Mazari, 1993; Caitcheon *et al*., 1995) or the volumes of sediment in flux in the drainage network (e.g. Walling, 1977, 1978), are often unable to identify the sources of the eroded sediment. Various types of chemical fingerprinting appear to be among the most successful techniques in identifying the sources of sediment in storage at depositional sites such as impoundments (e.g. Wasson *et al*., 1987; Caitcheon *et al*., 1995) or meander cutoffs (e.g. Bishop *et al*., 1992), but such identification is by no means the rule.

In small catchments that apparently exhibit only one type of erosion (gullying, for example), the investigation of volumes of post-impoundment sediment accumulation in small reservoirs offers one way of determining both the rate of erosion and the source of sediment (e.g. Neil and Fogarty, 1991). This approach relies on the assumption that the bulk of the impounded sediment can be attributed to the single form of erosion in the catchment. The literature on sedimentation of lakes, reservoirs and other impoundments does not necessarily warrant such an assumption, however, as the impoundment's catchment may have manifold sources of sediment, both allochthonous and autochthonous (Dearing and Foster, 1986). In a catchment that is apparently being eroded exclusively by, for example, gullying, allochthonous sources could include sheet erosion, which may be effectively invisible; aeolian accessions are another form of allochthonous sediment in an impoundment. Autochthonous sediments include chemical precipitates, as well as sediments produced by shoreline erosion and redistribution within the impoundment's water body. It is appropriate to include chemical precipitates in erosional studies because any dissolved load flowing into the lake or reservoir is likely to have been derived from catchment weathering and erosion, but sediment resulting from aeolian accessions and wave erosion of the shoreline should not be included in erosional studies.

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Measurement of the volumes of sediment trapped in small reservoirs is, nonetheless, a long-standing and evidently well-accepted method for determining erosion rates in small catchments (Langbein and Schumm, 1958; Le Roux and Roos, 1982; Neil and Galloway, 1989; Neil and Fogarty, 1991; Neil and Mazari, 1993). Small farm dams are particularly attractive for such determinations for at least two reasons:

- they are logistically easy to deal with because they trap sediment from small catchment areas which generally have high sediment delivery ratios, resulting in relatively rapid sedimentation of the impoundment, which can be determined easily and efficiently by one or two people (Neil and Galloway, 1989); and
- they provide data for small catchment areas that can be compared with data from instrumented small catchments.

The information provided by small impoundment sedimentation is important not only in its own right for understanding rates of erosion in small catchments, but also because farm dam sedimentation has significant economic implications (Lloyd *et al*., 1996) and because the proliferation of farm dams across rural landscapes may eventually constitute an important disruption to the delivery of water and sediment to higher order streams (Srikanthan and Neil, 1989).

It is generally assumed in using farm dam sedimentation surveys for determining catchment erosion rates that the sediment stored in the impoundment has been derived exclusively from mechanical (physical) erosion of the catchment. This assumption usually remains unstated and is rarely (if ever) assessed. As already noted, other possible sources of sediment include aeolian accessions, wave erosion of the dam shoreline and chemical precipitates. A further source of farm dam sediment that is unrelated to catchment erosion processes, and which evidently has not been recognized in the literature, is erosion of the dam shoreline due to foraging and trampling of the shoreline by livestock. This paper reports the use of hillcrest farm dams in the Strzelecki Ranges of South Gippsland, SE Australia, to assess the contribution to farm dam sedimentation of shoreline erosion due to livestock activity.

FIELD SITE AND METHODOLOGY

The study was undertaken in the Lance Creek catchment, in the foothills of the Strzelecki Ranges, South Gippsland (Figure 1). The area is characterized by steep slopes formed on Cretaceous mudstones and sandstones, and soils are predominantly yellow chromosols (yellow duplex soils) with highly dispersive subsoils (Hart *et al*., 1992).

The area has been extensively cleared over the 150 years of European settlement, and current land use is dominated by the grazing of beef and dairy cattle. The region’s rainfall, averaging 976 mm per annum (data from Wonthaggi/Inverloch Water Board, 1994), provides ample water for the 242 farm dams (average size 30 m by 30 m) that currently catch and store rainfall and runoff for stock watering in the 2000 ha catchment. Many of these dams are on hillcrests and have virtually no catchments, and others on hillslopes likewise have minimal or virtually no catchment areas. Hillcrest impoundments receive no runoff, being replenished only by direct rainfall, thereby providing an excellent opportunity to investigate rates of erosion of farm dam shorelines by cattle that have access to the dams for drinking water (Figure 2). Essentially all of the sediment deposited in the hillcrest dams surveyed can be attributed to such shoreline erosion. The hillslope dams surveyed in this study can be treated in the same way as they have minimal catchment areas. This assumption is reasonable given the evident lack of erosion in their catchments.

Two hillcrest impoundments with no catchment areas and five impoundments with minimal hillslope catchments (average catchment area of only 0.5 ha) were selected for the study; three dams with gullied catchments were also examined for comparison with the hillcrest and hillslope dams (Figure 1; Table I). Sediment accumulated in the hillcrest dams can only have been derived from aeolian accessions and/or shoreline erosion by wave action and livestock trampling, and this can be safely assumed for the hillslope dams because they have minimal catchment areas. The contribution of aeolian dust to both types of impoundments is considered to be negligible, given the high rainfall of the area and the almost complete, year-round pasture coverage of the catchment. Likewise, the contribution from erosion of the shorelines by wind waves alone, without prior trampling of the shoreline by livestock, is thought to be minimal because of the short fetch lengths

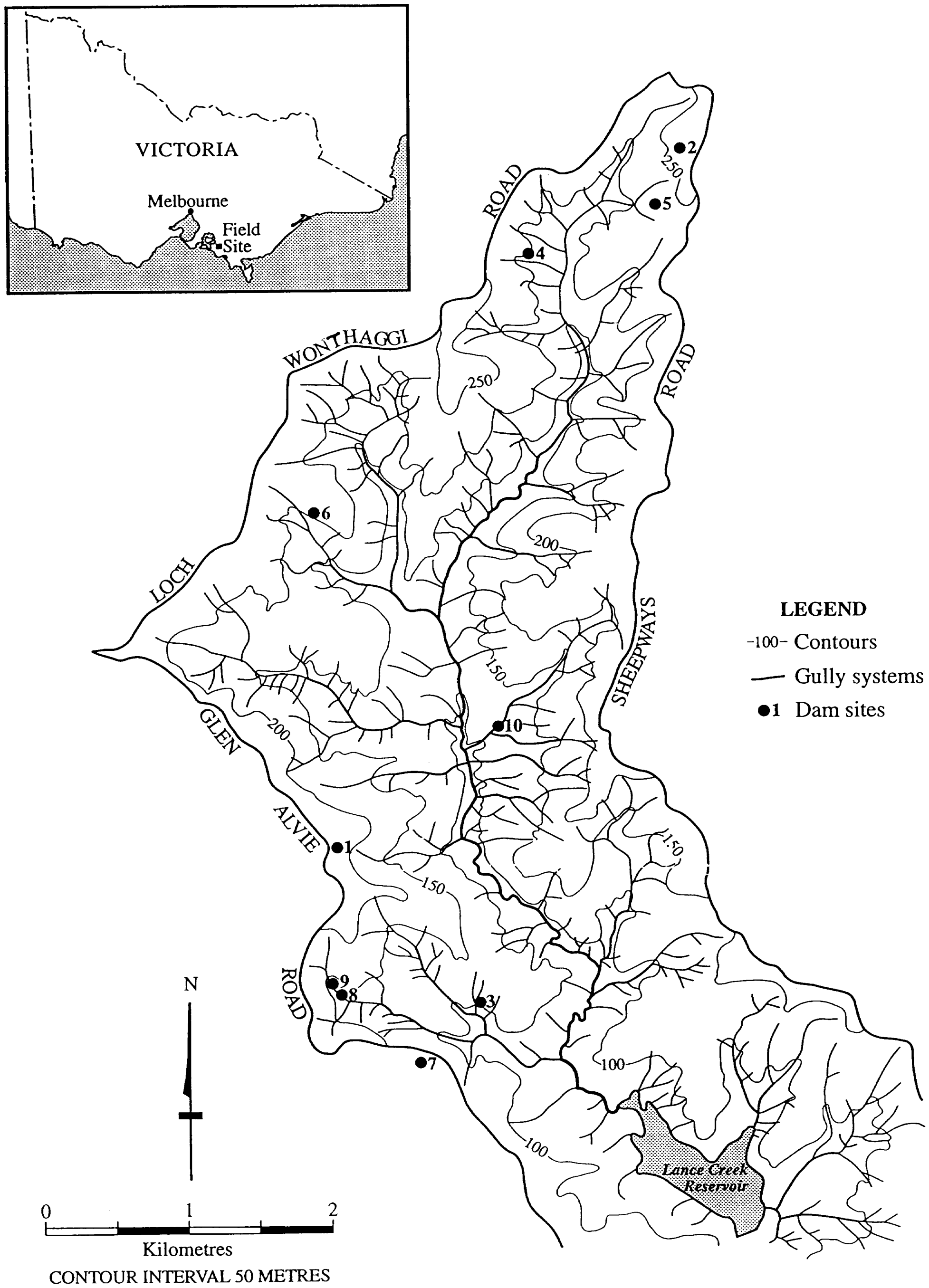

Figure 1. The Lance Creek catchment study area in SE Australia.

of these water bodies. This means that virtually all of the sediment in these dams must have been derived from shoreline erosion as a result of livestock trampling. Sediment accumulated in the dams in gullied catchments has been derived also from the gully systems and, in the case of dams 8 and 9, from the occasional cropping in their catchments. We assume, on the basis of information from landowners, that livestock access to all 10 impoundments has been essentially equal.

Figure 2. Livestock standing in small farm dam. Note the steepness of the shoreface as a result of erosion due to livestock access. The calculation of the volume of shoreline erosion is illustrated by the annotated dimensions of the severely eroded shoreline length behind, and to the immediate right of, the animal. The volume of eroded shoreline is the product of the length (L), average width (W), and average height (H) of the eroded segment (in this case = $5{\cdot}5\,m \times 0{\cdot}7\,m \times 0{\cdot}8\,m = 3{\cdot}1\,m^3$).

Table I. Farm dam characteristics

Dam	Location	Age (a)	Catchment area (ha)	Shoreline length (m)	Heinemann (1981) trap efficiency (%)	Major source areas of sediment
1	Hillcrest	21	N/A	85	100	Shoreline
2	Hillcrest	0·5	N/A	81	100	Shoreline
3	Hillslope	12	1·2	107	90	Shoreline (+ minor hillslope?)
4	Hillslope	7	0·4	93	98	Shoreline (+ minor hillslope?)
5	Hillslope	30	0·2	77	89	Shoreline (+ minor hillslope?)
6	Hillslope	5	0·8	101	94	Shoreline (+ minor hillslope?)
7	Hillslope	10	N/A	106	100	Shoreline
8	Gully	10	1·7	86	70	Shoreline/gully/cultivated hillslopes
9	Gully	8	1·6	60	36	Shoreline/gully/cultivated hillslopes
10	Gully	24	13·1	129	59	Shoreline/gully/hillslopes

N/A, not applicable

Sampling of the sediment thicknesses in the dams followed the general approach of Neil and Galloway (1989) but used a regular $5\,m \times 5\,m$ survey grid. The grid was laid out by stretching ropes and attached measuring tapes across the water surface. Sediment cores were obtained from an inflatable dinghy (Zodiac) at each grid intersection using a clear perspex, soft-sediment–water interface sampler (36 mm external diameter, 32 mm internal diameter) with a piston with a self-closing aluminium valve top (Figure 3). The clear perspex coring barrel permitted visual recognition of the accumulated sediments and the underlying (pre-impoundment) substrate. This substrate was readily identified by its gleyed colouring, coarser texture and the presence of rock fragments. The substrate material formed a natural plug at the base of the core and allowed easy recovery of the cores into the dinghy.

The thickness and characteristics of the sediment in each core were recorded in the field before the sediments were extruded from the barrel and bagged for later density determinations in the laboratory. Two sediment types were typically identified in each core and bagged separately: (i) basal brown to black semicompacted muds, overlain by (ii) a dark reddish-brown flocculated mud layer. Following common practice (Neil and Galloway, 1989), the thickness of accumulated sediments was not corrected for the inclusion of water, gas and

Figure 3. Coring from the Zodiac dinghy at a grid intersection point in a hillcrest dam.

organic matter. The organic fraction was removed in the laboratory using the standard method (hydrogen peroxide), as described by McTainsh *et al*. (1989). Densities were determined for each sediment type using the sediment's dry weight and its volume (based on the thickness of each sediment type and the internal diameter of the coring barrel).

The thicknesses and mean densities of each sediment type in the seven dams with minimal or no catchment areas, and the areas of each of these dams, were used to compute the total mass of sediment in each dam. The rate of shoreline erosion for each dam was then found using the equation:

$$ER = (M \times 100)/(TE \times P \times A)$$

where ER is the shoreline erosion rate in tonnes of sediment eroded per metre of shoreline per year ($\mathrm{t\,m^{-1}\,a^{-1}}$), M is the mass (t) of sediment in the dam (based on average densities of approximately $240\,\mathrm{kg\,m^{-3}}$ for the flocculated muds at the top of the sediment accumulation and $595\,\mathrm{kg\,m^{-3}}$ for the underlying compacted muds), TE is the trap efficiency (per cent), P is the dam perimeter (shoreline) length (m), and A is the age of the dam in years (provided by the landowners). Sediment thicknesses are typically less than 15 cm and the low values of the densities of the depositied sediments evidently reflect the minimal compaction of the sediments.

Each impoundment's trap efficiency (TE: the efficiency in trapping and retaining all of the sediment delivered to the dam by catchment erosion processes and inflow) was determined from the Heinemann (1981) trap efficiency curve. This curve, like the earlier one derived by Brune (1953), is based on data from large reservoirs of unclear applicability to small (low capacity) farm dams draining small catchments with highly variable, and often very peaked, hydrographs. Despite this uncertainty, the published trap efficiency relationships continue to be used in small farm dam sedimentation studies (e.g. Le Roux and Roos, 1982; Neil and Galloway, 1989; Neil and Fogarty, 1991; Neil and Mazari, 1993), and we followed the same approach here with the important modification of adopting a range of trap efficiency values for each dam. A single value for the trap efficiency of small farm dams is intuitively inappropriate because the trap efficiency of such small, low capacity impoundments is likely to be highly dependent on inflow characteristics, which may vary with different rainfall events. Two arbitrarily lower trap efficiency values (50 per cent and 20 per cent) were therefore also used in the calculations (Table II). It is worth noting in passing that the various uncertainties associated with extrapolating trap efficiencies derived from large reservoirs to small farm dam studies mean that erosion rates that rely on its use should be treated as indicative only. Such erosion rates are probably of most use for assessing relativities of erosion rates, and should not be taken to be estimates of the 'true' rates.

Table II. Farm dam shoreline erosion rates in dams 1–7 (dams with minimal or no catchment areas)

Dam	Location	Mass of sediment (t)	Shoreline erosion rate ($t\,m^{-1}\,a^{-1}$)		
			Using Heinemann trap efficiency (Table I)	Using 50% trap efficiency	Using 20% trap efficiency
1	Hillcrest	33·4	0·02	N/A	N/A
2	Hillcrest	1·4	0·03	N/A	N/A
3	Hillslope	12·9	0·01	0·02	0·05
4	Hillslope	7·2	0·01	0·02	0·06
5	Hillslope	14·4	0·01	0·01	0·04
6	Hillslope	8·5	0·02	0·03	0·08
7	Hillslope	31·7	0·03	N/A	N/A

N/A, not applicable

RESULTS

Table II shows that the rate of shoreline erosion is from 0.01 to 0.03$t\,m^{-1}\,a^{-1}$, using Heinemann (1981) trap efficiencies. It is interesting to note that the estimated shoreline erosion rates for the hillslope dams 3, 4, 5 and 6, the dams with the largest of the 'minimal' catchment areas, are generally lower than the rates determined from the hillcrest dams and hillslope dam 7 (which, with its very small catchment area, is here treated as essentially equivalent to a hillcrest dam). This suggests either that hillslope dams 3 to 6 inclusive have had less intensive visitation and shoreline erosion by stock, or that they have lost by overflow some of the stored sediment eroded from their shorelines. The farmers' indications (and our corresponding assumption) that rates of stock visitation did not vary between dams mean, therefore, that these dams have lost sediment by overflow and that the Heinemann (1981) trap efficiency estimates for the hillslope dams (all greater than 89 per cent) are almost certainly too high. In effect, inflows from the catchments of dams 3, 4, 5 and 6 have evidently resulted in some flushing of sediment from these dams and shoreline erosion rates calculated for these hillslope dams are therefore minima.

Trap efficiencies of 50 per cent in the hillslope dams yield shoreline erosion rates closer to those calculated for hillcrest dams (Table II), confirming that the Heinemann curve probably over-estimates the trap efficiencies of the hillslope dams in this study. Conversely, a trap efficiency of 20 per cent yields an apparent rate of shoreline erosion in the hillslope dams greater than the rates calculated for hillcrest dams, implying that if indeed these hillslope farm dams are only 20 per cent trap efficient then some sediment is being transported from the dam's catchment into the dam. Detailed field investigation revealed no obvious source of erosion in the catchments of these hillslope dams, and it is therefore most likely that the dams trap a greater proportion than 20 per cent of the incoming sediment. Until intensive monitoring during overflow events is undertaken, a degree of uncertainty will always surround the issue of trap efficiency in studies such as this.

Assuming that the trap efficiency values for the hillslope impoundments are between 50 and 100 per cent, the average rate of shoreline erosion determined for dams 1 to 7 is 0.02$t\,m^{-1}\,a^{-1}$ (Table II). This average rate of shoreline erosion was assumed to be applicable to dams 8, 9 and 10 (in gully systems) and used to determine the mass of sediment that could be attributed to shoreline erosion in each of these dams. Of the total amount of sediment in dams 8 (46·6 t), 9 (11·3 t) and 10 (150·5 t), shoreline erosion of 0.02$t\,m^{-1}\,a^{-1}$ can account for 17·2 t of the sediment in dam 8 (37 per cent), 9·6 t (85 per cent) in dam 9, and 61·9 t (41 per cent) of the sediment in dam 10. In relative terms, the rate of sediment production by shoreline erosion is of the same order of magnitude as sediment production by gully erosion.

These results show that a substantial proportion of the sediment stored in all dams can be attributed to shoreline erosion rather than to catchment erosion processes. Figure 4 highlights how the failure to take account of the effects of shoreline erosion results in exaggerated estimates of catchment erosion rates. Even if our assumption that livestock visited all farm dams in this study at the same rate is not completely accurate, the uncertainties associated with the demonstrated erosion of farm dam shorelines by livestock prompt caution when estimating rates of catchment erosion on the basis of volumes of sediment in such dams.

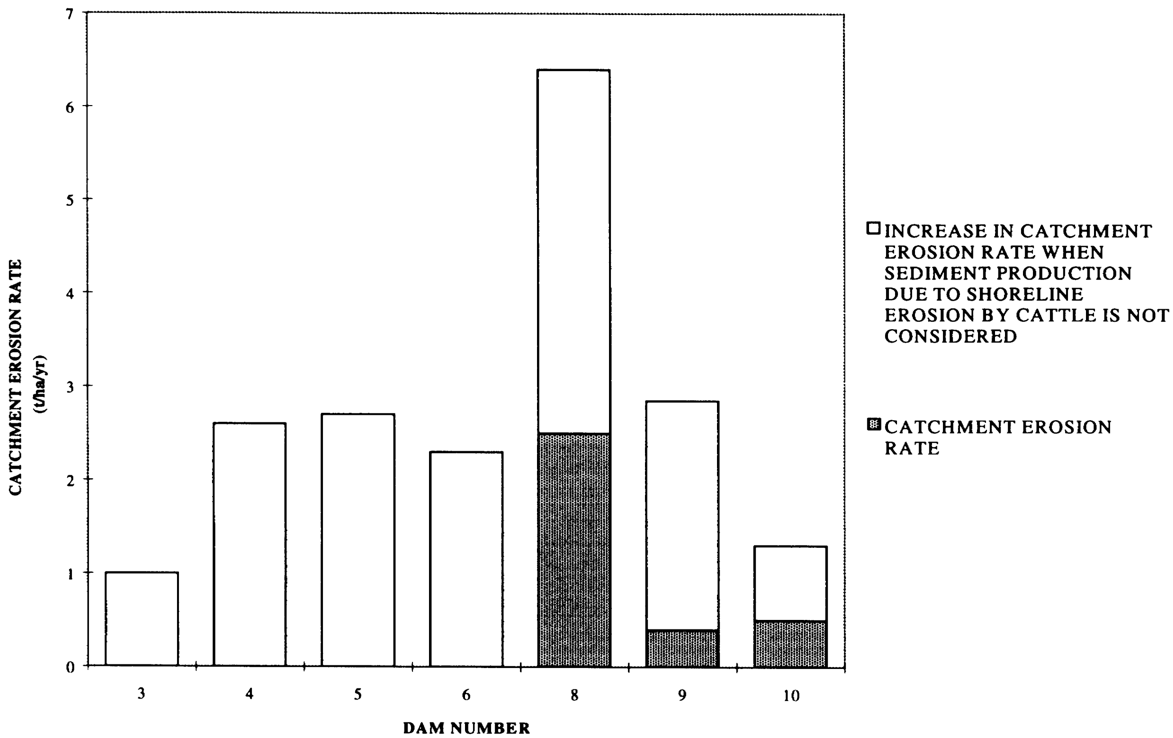

Figure 4. Apparent increases in catchment erosion rates due to contributions to sediment volumes in farm dams from shoreline erosion.

CONCLUDING DISCUSSION

It is already well known from the river management literature that livestock can be responsible for significant erosion at the waterline along stream banks; indeed, management guidelines for stream banks regularly include a recommendation that livestock be excluded as much as possible from access to the stream (e.g. Outhet, undated). A number of studies has shown that stream bank erosion under such circumstances is due primarily to trampling and the removal of forage along the waterline (Kauffman *et al*., 1983; Kauffman and Krueger, 1984; Trimble, 1994; Trimble and Mendel, 1995). Cattle are believed to have the most detrimental impacts of all grazing livestock because of their greater weight and their more frequent return to the same site to drink (Platts, 1991). Large volumes of sediment are generated at the river waterline by the ‘pugging’ of sediment and soil by livestock at the water’s edge, forming a plume of sediment that moves downstream. These processes are equally relevant to farm dam shorelines and evidently promote significant accessions of sediment to farm dams to which livestock have unrestricted access.

Such sediment and the associated loss of storage capacity (as well as the nutrient enrichment of the dam water by fine-grained sediments and livestock excreta) have significant implications for the life of the dam and the quality of its water (Lloyd *et al*., 1996). More importantly for the present discussion, rates of erosion of small catchments which are based on the amounts of sediment in small farm dams, and which ignore accessions to the sediment held in the dam as a result of shoreline erosion by livestock, are liable to over-estimate such rates of erosion. This tendency to over-estimate rates of catchment erosion as a result of failure to take account of that proportion of sediment produced by shoreline erosion may be counteracted by the tendency to under-estimate sediment volumes as a result of the use of trap efficiency values that are too high. In any event, this study shows that the estimation of small catchment erosion rates from the volumes of sediment stored in small farm dams is subject to at least two sources of significant error: non-catchment sources of sediment such as shoreline erosion, and sediment loss from the dam.

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